ASTM INTERNATIONAL

Journal of
Testing and Evaluation

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DOI: 10.1520/JTE20150127

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Journal of Testing and Evaluation

doi:10.1520/JTE20150127 available online at www.astm.org

TECHNICAL NOTE

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Evaluation and Comparison of Double Clip Gauge Method and Delta 5 Method for CTOD Measurement in SE(T) Specimens

Manuscript received March 26, 2015; accepted for publication September 16, 2015; published online November 24, 2015.

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Reference

Van Minnebruggen, Koen, Verstraete, Matthias, Hertelé, Stijn, and De Waele, Wim, "Evaluation and Comparison of Double Clip Gauge Method and Delta 5 Method for CTOD Measurement in SE(T) Specimens," *Journal of Testing and Evaluation* doi:10.1520/JTE20150127. ISSN 0090-3973

ABSTRACT

The experimental evaluation of the fracture toughness of line pipe steels and girth welds is increasingly performed through single edge notched tensile—SE(T)—testing. The notch constraint in these specimens closely matches that in pipes. This paper focused on the measurement of the crack tip opening displacement (CTOD). The double clip gauge method and the GKSS δ_5 method were compared based on experimental tests on both welded and nonwelded specimens. A good correspondence between both techniques was observed. The δ_5 method tended to result in a slightly lower estimation of crack driving force, which was explained by the difference between both CTOD definitions. Both techniques were concluded to be equivalent for the evaluation of CTOD in SE(T) specimens.

Keywords

crack tip opening displacement, double clip gauge method, delta 5 method

Nomenclature

a = flaw depth (mm)
a_0 = initial flaw depth (mm)
a_{final} = final flaw depth (mm)
B = thickness (mm)
B_N = net section thickness (mm)
CTOD = crack tip opening displacement (mm)
CMOD = crack mouth opening displacement (mm)

DIC = digital image correlation
H = daylight grip length (mm)
MM_{FS} = flow strength mismatch
SE(T) = single edge notched tensile test specimen
t = wall thickness (mm)
W = height (mm)
WMC = weld metal center
Y/T = yield-to-tensile ratio
δ_0 = CTOD measured at the original crack tip location (mm)
δ_5 = CTOD measured using two points located 5 mm apart, across the crack tip (mm)
δ_{90° = CTOD evaluated using double clip gauge and 90° intercept definition (mm)

Introduction

As contemporary line pipe steels are typically of high toughness, their fracture toughness cannot be characterized by means of a critical elastic stress intensity factor (*KIc*). In turn, elastic-plastic fracture mechanics (EPFM) theory applies. A material's fracture toughness at a given level of crack tip constraint can be characterized by its tearing resistance curve. This so called R-curve presents the crack tip loading as a function of the ductile crack extension (Δa) (mm). The crack tip loading can be expressed in terms of the J-integral (J) (kJ/m^2) or crack tip opening displacement (CTOD) (mm). From a theoretical perspective, both CTOD and the J-integral yield similar outcomes [1,2]. Both parameters have been widely used as fracture mechanics parameters and are considered to be interchangeable in EPFM [3].

For pipeline applications, single edge notched tensile—SE(T) as defined in ASTM E1823-13 [4]—specimens have been shown to closely match the notch constraint in pipes, provided their relative crack depth matches that of the assessed pipe defects [5–7]. Therefore, the SE(T) specimen is considered to be a suitable small-scale testing solution to determine the tearing resistance parameters. The evaluation of ductile crack extension in SE(T) specimens is typically obtained from reliable techniques such as unloading compliance [8] or dc potential drop measurements [9]. This paper focuses on the measurement of the second constituent of an R-curve, i.e., the crack tip loading. This constituent can be expressed by (1) the J-integral obtained from the plastic work based on the crack mouth opening displacement (CMOD) or the load line displacement, (2) the CTOD derived from J [10], or (3) a direct measurement of the CTOD as proposed by ExxonMobil [11] and GKSS [12] among others. In this paper, direct CTOD measurement techniques are compared.

A number of techniques are available for the experimental quantification of crack tip loading in terms of CTOD. The available techniques can be divided into two groups. First, the evaluation of CTOD can be based on measurements acquired at the crack mouth, i.e., the CMOD. Secondly, the evaluation can be based on the deformation of the specimen's surface perpendicular to the crack mouth, i.e., the side of the specimen. To the author's knowledge, no experimental comparison of both techniques has been performed for SE(T) specimens.

Therefore, this paper aims at presenting a generally applicable method for the evaluation of the crack tip loading in SE(T) specimens. This enhances the comparability of the test results and eliminates potential differences due to distinct measurement errors and challenges inherent to the applied methods.

Crack Tip Opening Displacement

For standardized fracture mechanics specimens, the CTOD is often determined using a single clip gauge located at the crack mouth [13]. This is an approximate method that relies on a numerical estimation of the location of the plastic hinge. An alternative method, also based on the plastic hinge model, is the double clip gauge method, which was first proposed in the 1980s [14,15] and which recently gained interest in SE(T) testing [16–19]. In this paper, the double clip gauge method is combined with the 90° intercept definition of CTOD, further denoted as δ_{90°, starting from the original crack tip, whereby a_0 equals the depth of the original crack (**Fig. 1**). From the readings of the two clip gauges mounted at different heights above the surface, the CTOD is calculated (for a more detailed description, see the Double Clip Gauge Method section). It is thereby assumed that the original crack faces do not deform plastically but instead behave as rigid arms rotating around a point [20].

Whereas the previous method relies on the 90° intercept method, the CTOD can also be defined as the displacement of two reference points located at a fixed distance across the crack

FIG. 1 Illustration of CTOD definitions.

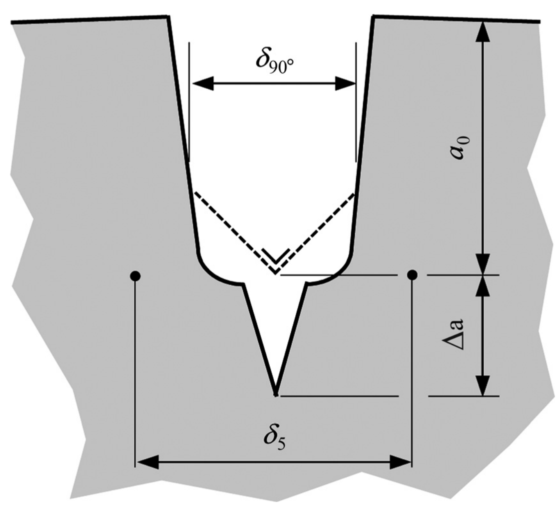
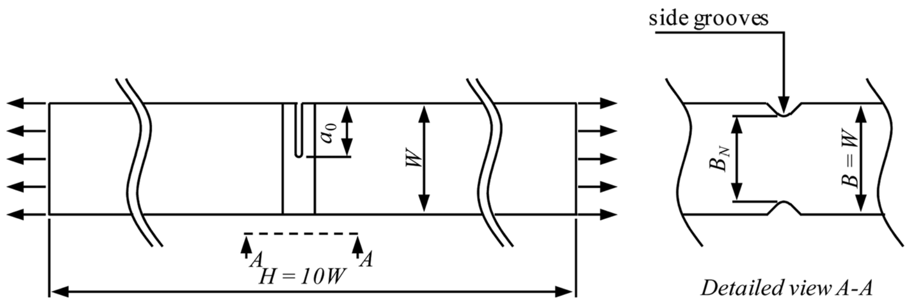


FIG. 2
Schematic representation of SE(T) specimen.



tip. Such a definition was developed by Helmholtz-Zentrum Geesthacht (formerly GKSS) during the 1990s. They defined the CTOD as the displacement of two reference points placed 5.0 mm apart and across the crack tip, hence the term δ_5 [12] (**Fig. 1**).

Materials and Specimens

The SE(T) specimens considered in this work have a square cross section (i.e., thickness (B) over width (W) ratio equals unity, $B/W = 1$) and a daylight grip length (H) equal to $10W$ (**Fig. 2**). This configuration was chosen in preference to the over-square specimens ($B/W = 2$) because of the lower required test capacity. Furthermore, note that a comparative study indicated no significant difference on resistance curves between the square and over-square specimens [21].

A notch is introduced through fine milling, which resulted in an initial notch root radius of 0.075 mm. Fatigue precracking is not applied. This would complicate the control of the initial crack depth and is not required for sufficiently ductile materials (e.g., ExxonMobil test procedure for SE(T) testing [11] and Akourri et al. for SE(B) specimens [22]).

V-shaped side grooves are machined at both sides of the test specimen to promote uniform crack extension. A total thickness reduction of 15 % (B_N = net thickness = $0.85W$) is achieved as advised by Shen et al. [23]. These side grooves conform to ASTM E1820 requirements, i.e., they have an opening angle less than 90° and a root radius of 0.5 ± 0.2 mm [9]. The specimens are clamped using hydraulic grips mounted in a 150 kN tensile test rig and loaded in displacement rate control (0.01 mm/s).

The test material can be divided in nonwelded and welded specimens, numbered "BM-xx" and "WM-xx," respectively (listed in **Table 1**). The nonwelded specimens are machined from an API-5L grade X80 pipe and have varying relative initial crack depths ranging between $a_0/W = 0.2$ and $a_0/W = 0.6$. The welded specimens are taken from two grade API-5L X80 pipes. The weld metal strength properties of the first set of three specimens closely matches the pipe metal properties (mismatch on flow strength, $MM_{FS} = +1.0$ %); for the second

TABLE 1 Overview of homogeneous and welded SE(T) specimens.

Specimen	$W = B$ (mm)	a_0/W (–)	API-5L Grade	Y/T_{BM} (–)	Y/T_{WM} (–)	Notch Location	Welding Process	MM_{FS} (%)
BM-01 BM-02	15.0	0.2	X80	0.86	–	base metal	Nonwelded	0
BM-03 BM-04	15.0	0.4	X80	0.86	–	base metal	Nonwelded	0
BM-05 BM-06	15.0	0.6	X80	0.86	–	base metal	Nonwelded	0
BM-07 BM-08 BM-09	15.0	0.5	X80	0.86	–	base metal	Nonwelded	0
WM-01 WM-02 WM-03	12.5	0.5	X80	0.91	0.83	WMC root	SMAW	+1
WM-04 WM-05 WM-06	12.5	0.5	X80	0.91	0.93	WMC root	GMAW	+33

set, these strongly overmatch the pipe strength properties ($MM_{FS} = +33$ %).

Measurement Methods

δ_5 METHOD

To monitor the deforming specimen, a two-camera stereoscopic system delivered by Limess GmbH is used [24]. This standalone system allows 3D digital image correlation (DIC) with the devoted software package VIC-3D [25] (**Fig. 3(*b*)**). On the specimen's surface, a random high-contrast speckle pattern is applied [26]. As the specimen deforms, changes in the speckle pattern are monitored. By matching the grey-scale distributions within pixel subsets between two subsequent images, the deformation can be quantified at every point in the speckled area of interest (**Fig. 3(*a*)**). By means of derivation, the local strain values can be determined. The speckle pattern is obtained by first applying a layer of highly elastic white paint onto the surface of the specimen. Subsequently, black speckles are sprayed on top of this layer.

Two monochrome cameras with resolutions of 2486 by 1985 pixels are used. Depending on the field of view, an appropriate speckle size can thus be calculated. A characteristic field of view is 25 by 20 mm^2; therefore, the ideal speckle size (3 by 3 pixels as advised in Ref [26]) corresponds with a physical speckle size of 30 by 30 μm^2.

During a test, pictures of the specimen's surface, perpendicular to the crack mouth, are periodically taken. This allows us to determine the displacements in the x, y, and z directions, as defined in **Fig. 3(*c*)**. It is noted that there is a lack of correlation in the near vicinity of the crack due to the presence of side grooves. Therefore, only the areas above and below the side groove are analyzed. From the full-field deformation measurements, the x-displacements of two points located 5.0 mm apart, symmetrically with respect to the crack tip are used for the evaluation of δ_5 (**Fig. 1**).

The VIC-3D software allows for a spatial resolution of 0.01 pixels, i.e., approximately 0.1 μm. However, nonideal practical conditions limit the actual accuracy. Resolution, accuracy, and precision are defined as suggested in ISO 5725 [27].

FIG. 3 Comparison of subsets in subsequent images [25] (*a*), schematic representation of DIC setup (*b*), and definition of x, y, and z directions (*c*).

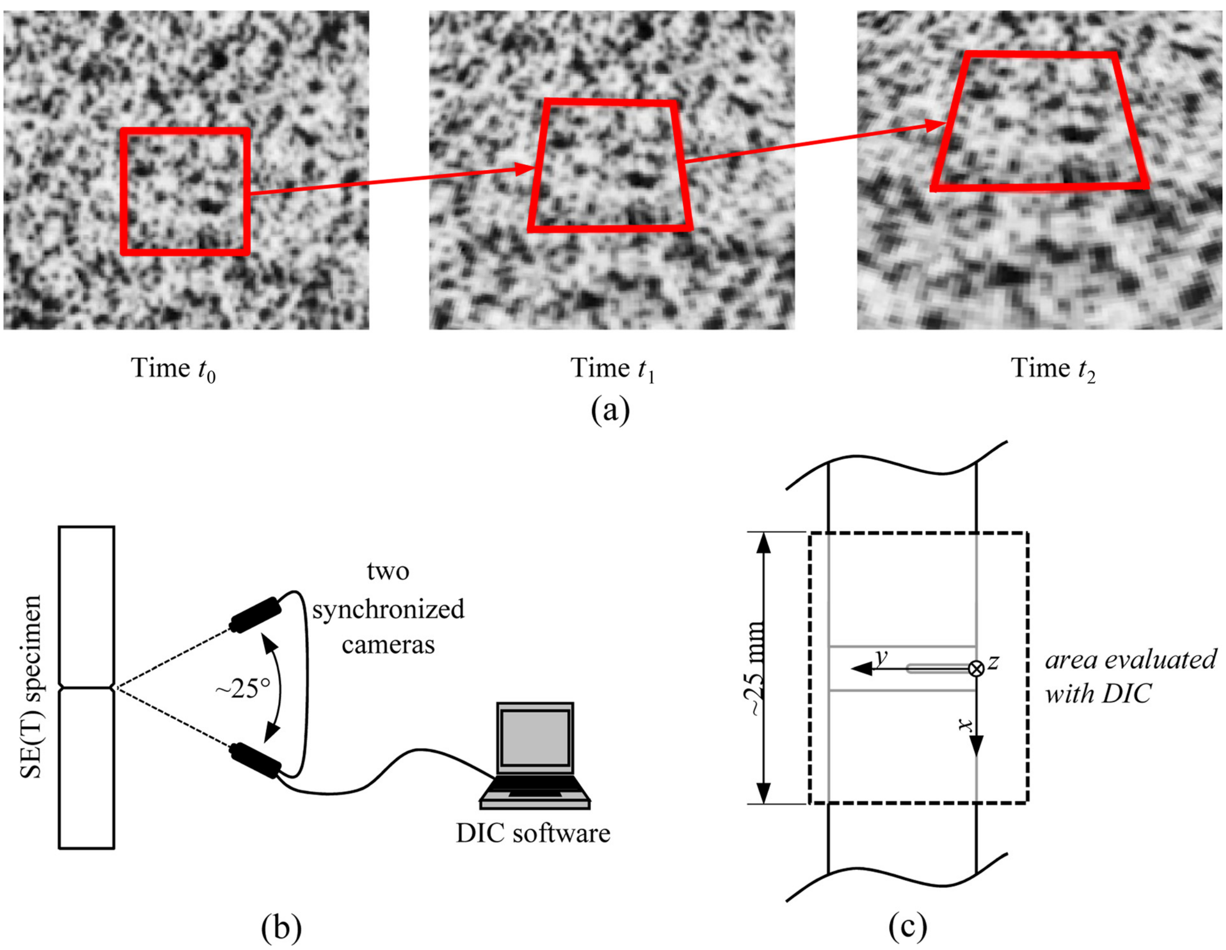
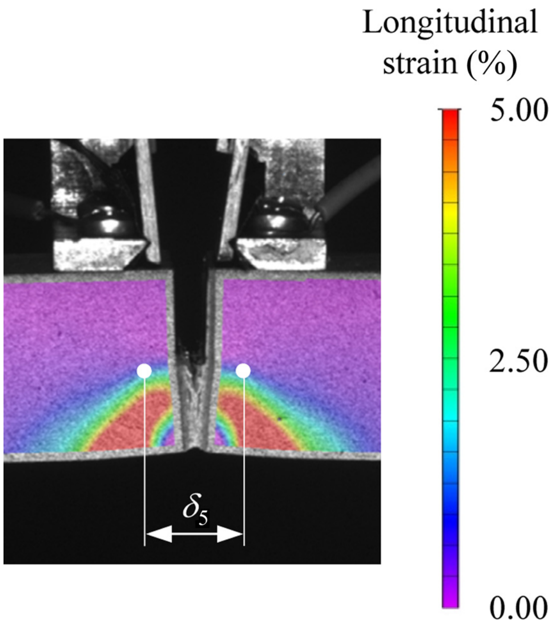


FIG. 4 Example case illustrating longitudinal strain field and location of the tracked points for the δ_5 method in test W01.

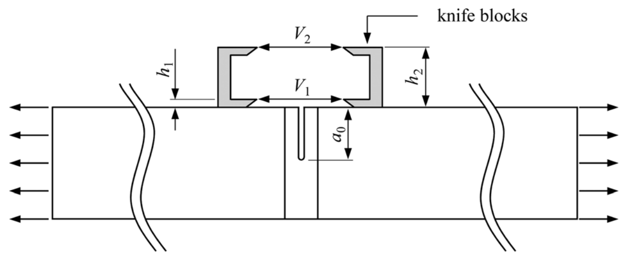


To evaluate the precision of this DIC-based method, the predicted distance between two points initially located 5.0 mm apart is calculated for multiple images of the undeformed specimen. From a total of 12 independent measurements, a standard deviation of 0.62 μm was calculated (measured extremes: $\delta_{5;min} - \delta_{5;max} = 1.98\ \mu$m). Hence, the presented method is sufficiently precise for evaluating the CTOD, which is typically in the range of (tenths of) millimeters.

One might argue that the local deformations around the crack tip potentially influence the δ_5 measurements. However, when evaluating the strain field (**Fig. 4**), it is clear that deformation is mainly localized at 45° shear bands originating from the crack tip. Furthermore, this figure indicates that even after significant ductile crack extension (i.e., approximately 1.7 mm), the strain in the zone of interest is limited. This observation applies to both welded and homogeneous specimens, which is well in agreement with the findings of Koçak [28]. He has shown that the δ_5 method does not require any adjustments to compensate for the potential influence of neighboring (strength mismatched) materials. The application of the δ_5 concept to a range of metals (e.g., steel, aluminum, austenitic stainless steel) has been demonstrated by GKSS [29,30].

For more elastic materials, the difference between δ_5 and $\delta_{90°}$ is expected to increase due to the influence of local deformations on δ_5. Here, the strain in the 5-mm measurement base for δ_5 could become significantly large in comparison with the actual crack tip opening. Additionally, these elastic contributions of CTOD are not accounted for in the calculation of $\delta_{90°}$ [12]. For example, the δ_5 method has been evaluated for fiber metal laminates by Castrodeza et al. [31]. They observed that δ_5 yielded lower values of CTOD, which is attributed to the underestimation of the elastic component of CTOD by the double clip gauge method, as it only takes the plastic component into account.

FIG. 5 Illustration of mounting pieces attached to a SE(T) specimen, allowing us to measure CTOD via the double clip gauge method.



DOUBLE CLIP GAUGE METHOD

Two small mounting pieces are screwed onto the specimen's notched top surface, facilitating the attachment of the clip gauges on the knife ends (**Fig. 5**). To that extent, two 3.0-mm-deep holes with a diameter of 1.9 mm are drilled at each side of the crack. Generally, these holes are located 4.5 mm apart from the cracked ligament, resulting in an initial clip gauge opening of 3.0 mm. The heights for the attachment of the clip gauges, h_1 and h_2, equal 2.0 and 8.0 mm, respectively. An accurate positioning of the knife edges is required for the validity of the measurement [11,32]. However, currently there is no standardized test procedure that quantifies the tolerances. The possible detrimental effects of a nonperfect symmetrical positioning of the knife edges make the δ_5 method a potentially more robust measurement technique.

From both clip gauge readings, V_1 and V_2, the CTOD can subsequently be calculated assuming a rigid rotation around a plastic hinge.

The opening at the original crack tip δ_0 is given by [11,32]

$$\delta_0 = V_1 - \frac{(a_0 + h_1)}{(h_2 - h_1)}(V_2 - V_1) \quad (1)$$

The CTOD at the 90° intercept, $\delta_{90°}$, is approximated by

$$\delta_{90°} = \delta_0 + \frac{\delta_{90°}}{2}\alpha \quad (2)$$

With α the crack flank angle,

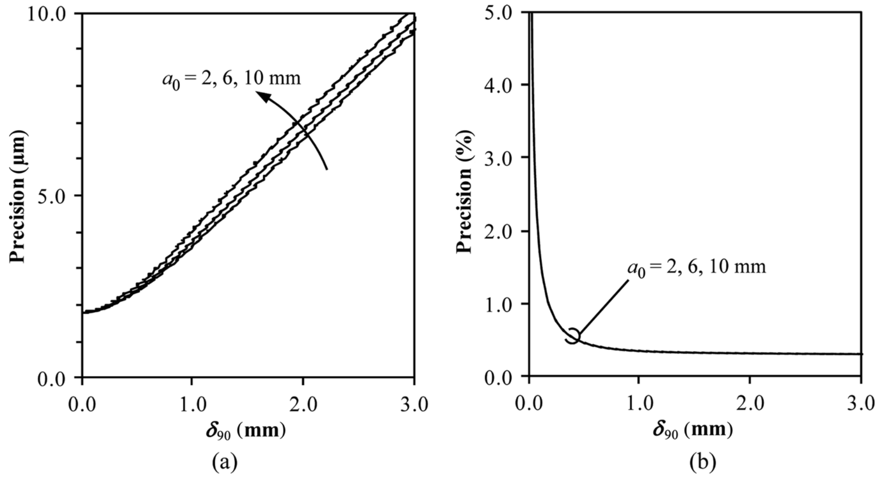
$$\alpha = \frac{V_2 - V_1}{h_2 - h_1} \quad (3)$$

Substitution of Eqs 1 and 3 into Eq 2 and solving for $\delta_{90°}$ results in the following equation for CTOD:

$$\delta_{90°} = 2\frac{V_2(a_0 + h_1) - V_1(a_0 + h_2)}{(V_2 - V_1) - 2(h_2 - h_1)} \quad (4)$$

FIG. 6

Evaluation of precision for SE(T) specimen with varying initial crack depths in absolute terms (*a*) and relative (*b*).



Both clip gauges have a precision of $\pm 1.0\ \mu$m. The accuracy of the height measurements for h_1 and h_2 is taken equal to the accuracy of the caliper used for measuring these distances (0.01 mm). Based on the accuracy of the z axis of the milling machine, the accuracy of the initial crack depth a_0 is also taken as 0.01 mm. Subsequently, the precision of the CTOD measurements can be evaluated at increasing CTOD levels (**Fig. 6(*a*)**). The precision is calculated based on the general formula for error propagation. Consider a general function q with parameters x_1 to x_n.

$$q = f(x_1, x_2, \ldots, x_n) \tag{5}$$

The uncertainty δq for q is calculated based on the known uncertainties of the parameters as

$$\delta q = \sqrt{\left(\frac{\partial q}{\partial x_1}\delta x_1\right)^2 + \cdots + \left(\frac{\partial q}{\partial x_n}\delta x_n\right)^2} \tag{6}$$

Replacing q with CTOD and x_1 to x_n with V_1, V_2, h_1, h_2, and a_0 allows us to calculate the precision of CTOD. It was shown that this precision is within the micrometer range [33]. In absolute terms, the error increases with an increase of the CTOD level. In relative terms, the measurement error is largest at the early loading stages. For a CTOD level of 0.10 mm, commonly considered for stress-based defect assessments [34,35], the precision is 1.75 % (**Fig. 6(*b*)**). However, for strain-based assessments, higher CTOD levels (up to a few millimeters) are typically reached [36], resulting in an error below 1 %.

The presence of the drill holes and screws used for the attachment of the knife blocks might potentially influence the crack behavior. The drill holes are not allowed to be located outside a zone contained by an angle of 90° starting from the crack tip [13]. However, this limitation is not possible for all a_0/W ratios. To evaluate the influence hereof, the deformation fields surrounding the crack are studied for both shallow

FIG. 7

Deformation pattern around crack tip in SE(T) specimens (B = W = 15 mm) with shallow (a_0/W = 0.2) (*a*) and deep (a_0/W = 0.6) notch (*b*) at equal CTOD load level ($\delta_{90°}$ = 0.2 mm).

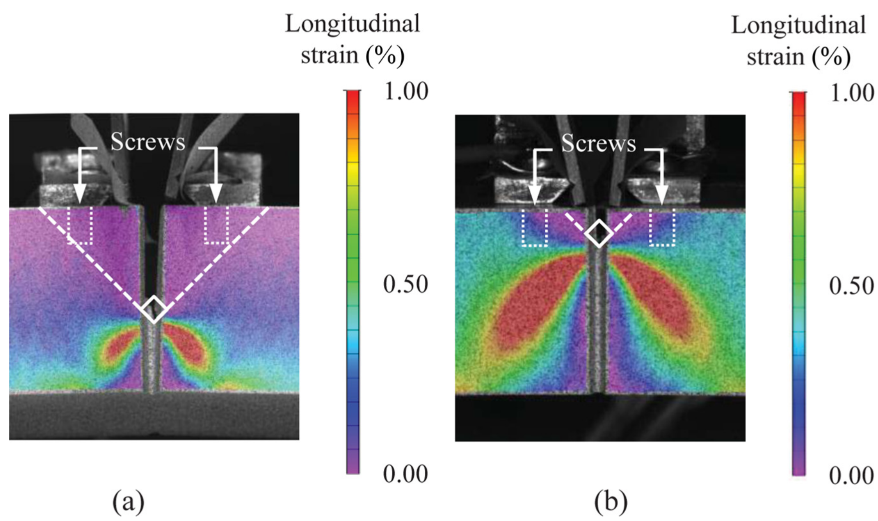
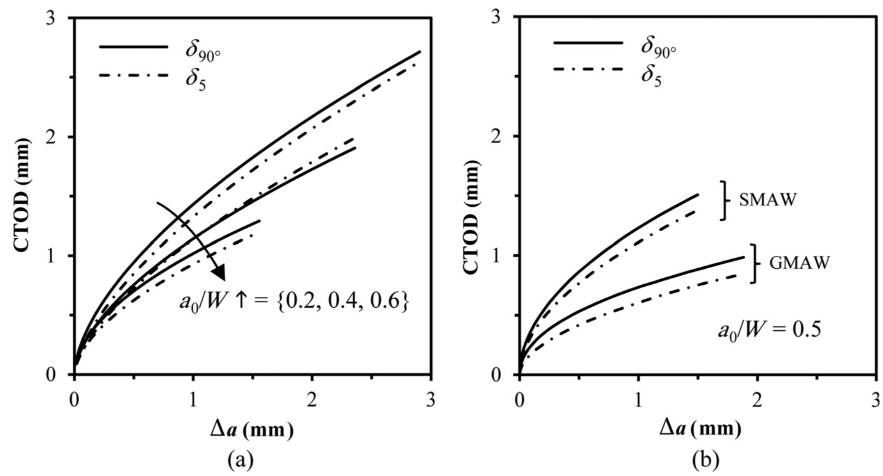


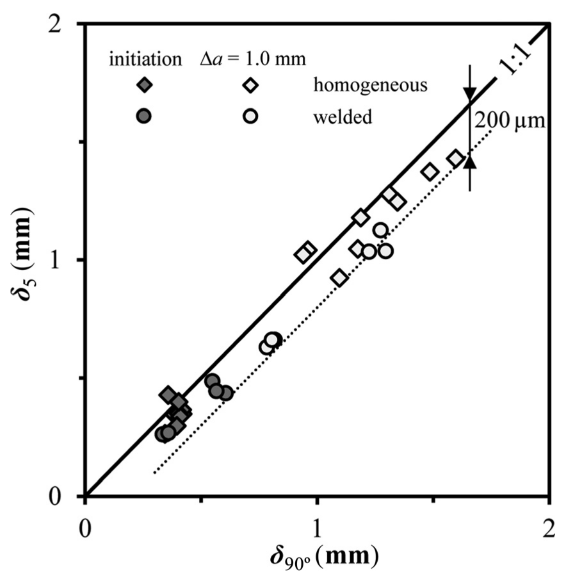
FIG. 8

Comparison of R-curves for specific tests for (*a*) base material with various initial notch size ratio and (*b*) weld metal with various welding procedures.



($a_0/W = 0.2$) and deeply ($a_0/W = 0.6$) notched homogeneous specimens based on full-field deformation measurements. The strain in the longitudinal direction at the specimen's surface is shown in **Fig. 7**. In addition, two dotted lines originating from the crack tip under 45° are plotted, and the screw positions are indicated. As expected, negligible deformation is observed within these 45° lines. For the deeply notched specimen, the deformation free zone is even more widespread. A similar trend was observed at higher load levels. Furthermore, the deformation pattern shows no irregularities that could indicate any disturbing effect of the screws. It is, therefore, concluded that the considered double clip gauge method has no influence on specimen deformation.

FIG. 9 Comparison of CTOD definitions in SE(T) tests: $\delta_{90°}$ versus δ_5.



Test Results

Both the δ_5 and $\delta_{90°}$ methods have been applied to a series of SE(T) tests as described in the Measurement Methods section, resulting in two resistance curves for each specimen. **Figure 8** illustrates five tests, the other tests show a similar behavior. It is observed that for each test both curves show a good agreement. The difference between these curves remains quasi-constant with increasing crack extension (as measured by the dc potential drop method [37]).

The influence of decreasing toughness with increasing relative initial crack size as illustrated in **Fig. 8(*a*)** is expected. The welded specimens are shown to be of lower fracture toughness compared with the tested base material samples (**Fig. 8(*b*)**).

To facilitate the comparison, both CTOD definitions are evaluated at crack initiation as defined by BS 8571-14 [38] and at 1.0 mm of ductile crack extension. The 1-mm crack extension is considered to be a representative comparison, as the difference between both curves remains quasi-constant for all tested specimens. **Figure 9** indicates an overall satisfactory correspondence between both.

Based on **Fig. 9**, it is observed that on average the CTOD values obtained by the $\delta_{90°}$ method are 86 μm larger (i.e., relative 12 %) with a standard deviation of 79 μm when compared to the δ_5 method.

For the homogeneous specimens, the following is observed:

- At crack initiation, $\delta_{90°} - \delta_5$ is on average equal to 44 μm (11 % relative, i.e., $1 - \delta_5/\delta_{90°}$) with a standard deviation of 52 μm.
- At 1 mm crack extension, $\delta_{90°} - \delta_5$ is on average equal to 61 μm (4 % relative) with a standard deviation of 98 μm.

For the welded specimens, the following is observed:

- At crack initiation, $\delta_{90°} - \delta_5$ is on average equal to 100 μm (22 % relative) with a standard deviation of 40 μm.

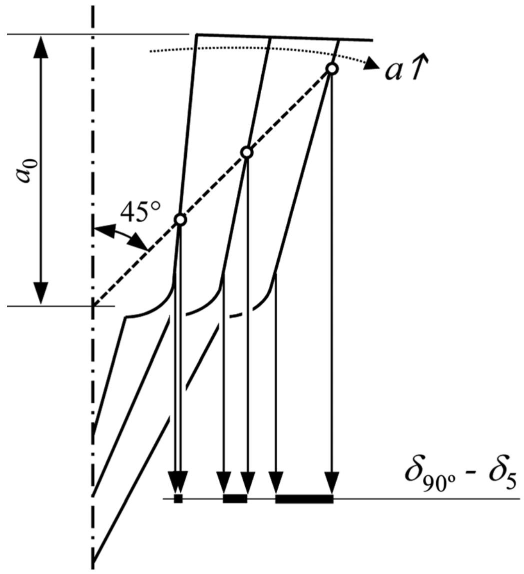


FIG. 10 Comparison of CTOD definitions in SE(T) tests: an illustration of difference between $\delta_{90°}$ and δ_5 for varying load levels.

- At 1 mm crack extension, $\delta_{90°} - \delta_5$ is on average equal to 173 μm (17 % relative) with a standard deviation of 44 μm.

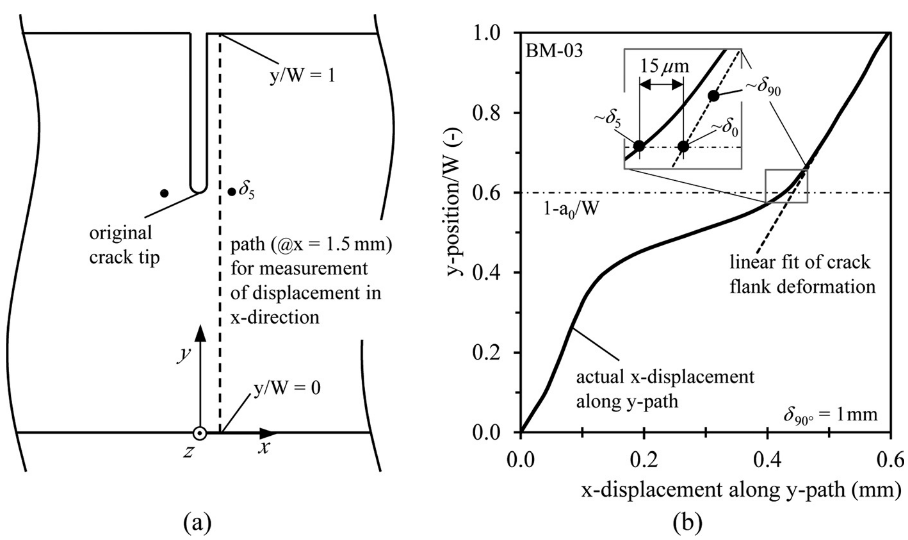
Based on the above, it is noted that the $\delta_{90°}$ method tends to predict higher CTOD values relative to the δ_5 method. This difference is inherent to the nature of both methods. Firstly, the δ_5 definition is based on a measurement of the opening at the initial crack tip, while the $\delta_{90°}$ measurement is taken at a certain height above the initial crack tip. As some unavoidable bending and rotation of the specimen is observed, $\delta_{90°}$ increases relative to δ_5. This effect furthermore results in increasing absolute errors at increasing CTOD levels since the CTOD is evaluated towards the crack mouth in this case (see **Fig. 10**). Secondly, the intercept method assumes the crack flanks to be linear for the extrapolation from the two clip gage readings, whereas in reality they are curved, thus, giving a smaller CTOD [39].

Figure 11 illustrates the actual deformation of the crack flanks upon loading of the crack tip for specimen BM-03 at a value of $\delta_{90°}$ equal to 1.0 mm.

The DIC technique is used for the determination of the deformation in the x direction of a path located 1.5 mm next to the original crack tip (**Fig. 11(*a*)**). This deformation is illustrated with the solid line in **Fig. 11(*b*)**, and the x-displacement at the position $y = 0$ is shifted to 0; thus, the curve has to be interpreted as a relative displacement. In the range $y/W = \{0.0\text{–}0.3\}$ the deformation is controlled by the restraint of the remaining ligament. In the range $y/W = \{0.7\text{–}1.0\}$, the absence of any restraint controls the deformation. This zone shows a good representation of the deformation of the crack flanks in the vicinity of the crack mouth. A transient zone is observed in the range $y/W = \{0.3\text{–}0.7\}$, which connects both zones resulting in a continuous deformation gradient. For the determination of δ_0 or $\delta_{90°}$, the straightness of the crack flanks is assumed, as indicated with the dashed line in **Fig. 11(*b*)**. Here it is observed that this assumption is incorrect in the vicinity of the original crack tip ($y/W = 1 - a_0/W = 0.6$), where the crack flanks are curved as expected [39]. The DIC methodology allows for a quantification of the error resulting from this assumption by subtracting the actual deformation (solid line) from the assumed straight deformation (dashed line). This is illustrated as a magnification (top in **Fig. 11(*b*)**) where the different CTOD definitions are indicated. As this illustration corresponds to half of the total deformation, the differences can be quantified: $\delta_0 - \delta_5 \approx 2 * 15\ \mu$m $\approx 30\ \mu$m, and $\delta_{90°} - \delta_0 \approx 2 * 10\ \mu$m $\approx 20\ \mu$m. Resulting in a total approximate difference for $\delta_{90°} - \delta_5$ of 50 μm, which corresponds

FIG. 11

Actual deformation in the x direction of a through thickness path. (*a*) Detail of SE(T) specimen with path at 1.5 mm next to the original crack tip indicated by dashed line. (*b*) Illustration of causes for differences between various CTOD definitions based on actual deformation of crack flanks.



closely to the average difference of 61 μm for the homogeneous specimens at 1.0 mm crack extension. This difference is observed to be quasi-constant for increasing CTOD levels, resulting in an equivalent observation as in **Fig. 9**. It is observed that the mechanism of nonlinearity of the crack flanks (as illustrated in **Fig. 11**) has a dominant effect on the difference between δ_{90° and δ_5 when compared to the specimen bending effect (as illustrated in **Fig. 10**).

In general, at initiation, the relative difference is large (approximately 20 %) due to the small values of CTOD. However, in absolute terms, the difference between both methods is limited to 60 μm. For the homogeneous specimens, both techniques are proven to be satisfactorily similar, as the relative difference is limited to approximately 6 %. At the moment of 1 mm crack extension, the relative difference is reduced due to the larger absolute values of CTOD, i.e., in absolute terms, the difference between both methods is limited to approximately 100 μm. For the welded specimens, larger differences are observed. This is expected from the heterogeneous nature of welds and the possible presence of weld defects. The δ_{90° is on average larger when compared to the δ_5 method for the determination of CTOD. This is expected from the unavoidable bending in the specimen (see **Fig. 10**) in combination with the actual deformation of the crack flanks, which is neglected for the case of the δ_{90° method (see **Fig. 11(*b*)**). The latter has shown to have a dominant effect.

Conclusions

Two methods have been considered for the evaluation of CTOD in SE(T) testing, namely, the double clip gauge method and the δ_5 method. For increasing load levels, the double clip gauge method yields slightly higher (100 μm on average) CTOD values. However, both methods show a strong correspondence (average difference is limited to 85 μm), in particular at crack initiation (i.e., 60 μm on average). In other words, the δ_5 method developed by GKSS and the double clip gauge method with a δ_{90° definition are equally suitable for the evaluation of CTOD upon crack tip loading in SE(T) specimens.

ACKNOWLEDGMENTS

The writers would like to acknowledge the financial support of the IWT (Agency for Innovation by Science and Technology—Grant Nos. SB-091512 and SB-093512) and the FWO (Research Foundation Flanders—Grant No. 1.5.247.08N.00).

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